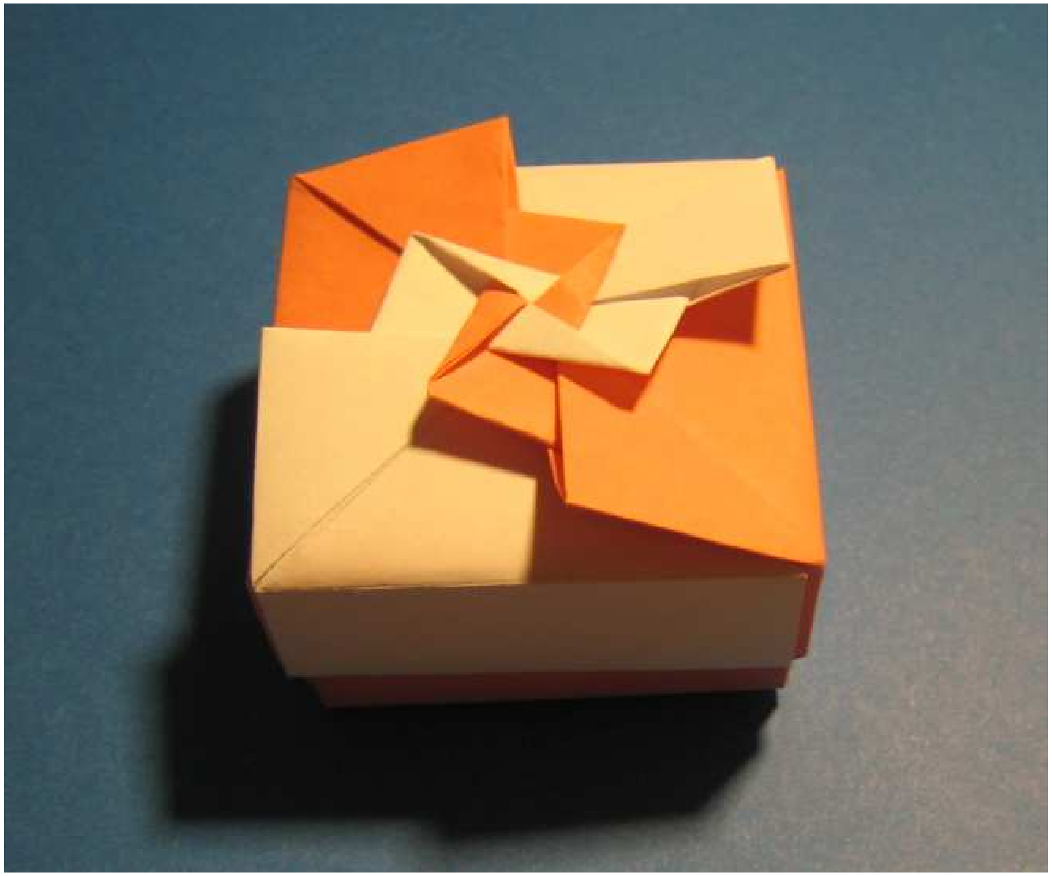
SHOWER MONTE CARLO + NLO: POWHEG

Carlo Oleari
Università di Milano-Bicocca, Milan

LoopFest IX
Stony Brook, 21 June 2010

- Shower Monte Carlo + NLO
- The POWHEG method
- The POWHEG BOX
- A few POWHEG results
- Conclusions



Shower Monte Carlo

- In high-energy collider physics not many questions can be answered without a Shower Monte Carlo (SMC).

- The name shower comes from the fact that we dress a hard event with QCD radiation.

- In general, the accuracy of SMC programs is Leading Order + Leading Log. They resum the largest logarithmic terms coming from the collinear (and soft) regions.

- Events are then characterized by a small number of high-p_T, well-separated, final-state partons (the ones described by the tree-level Born amplitude) + many collinear partons, whose collinear divergences have been correctly re-summed.

NLO

LO matrix elements are (often, but not always) good for shapes. Uncertain absolute normalization

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 + b_0\,\alpha_s(\mu_0)\log\left(\mu^2/\mu_0^2\right)}, \qquad b_0 = \left.\frac{11C_A - 4n_f T_F}{12\pi}\right|_{n_f=5} \approx 0.6$$

$$\alpha_s^n(2\mu) \approx \alpha_s^n(\mu)\left[1 - b_0\alpha_s(\mu)\log(4)\right]^n \approx \alpha_s^n(\mu)\left(1 - n\alpha_s(\mu)\right)$$

For $\mu = 100$ GeV, $\alpha_s = 0.12$, normalization uncertainty:

$W+1J$	$W+2J$	$W+3J$
$\pm 12\%$	$\pm 24\%$	$\pm 36\%$

To improve on this, we need to go to NLO

- Positive experience with NLO calculations at LEP, HERA and Tevatron
- NLO results are cumbersome to compute: typically made up of an n-body (Born + virtual + soft and collinear remnants) and $(n+1)$-body (real emission) terms, both divergent (finite only when summed up).

NLO vs Shower Monte Carlo

NLO

✓ accurate shapes at high p_T

✓ normalization accurate at NLO order

✓ reduced dependence on renormalization and factorization scales

✗ wrong shapes at small p_T

✗ description only at the parton level

SMC (LO + shower)

✗ bad description at high p_T

✗ normalization accurate only at LO

✓ correct Sudakov suppression at small p_T

✓ simulate events at the hadron level

It is natural to try to merge the two approaches, keeping the good features of both

- MC@NLO [Frixione and Webber, 2001]
- POWHEG [Nason, 2004]

POsitive-Weight Hardest Emission Generator

- ✓ POWHEG is a method for interfacing NLO calculations with parton shower programs [Nason, hep-ph/0409146]
- ✓ it generates the hardest emission first, with NLO accuracy, producing events with positive weights. The acronym comes from this feature
- ✓ The rest of the shower is performed by the (usual) LO Shower Monte Carlo programs, such as PYTHIA, HERWIG . . .
  It is then possible to compare the different outputs
- ✓ As far as the hardest emission is concerned, POWHEG guarantees
  - NLO accuracy on integrated quantities
  - collinear, double-log (soft-collinear), large-N_c-soft single-log of the Sudakov (in fact, corrections that exponentiates are obviously OK)
- ✓ The subsequent (less hard) emissions have the accuracy of the Shower Monte Carlo program one is using.

Existing implementations

Up to now, the following processes have been implemented using the POWHEG method:

- $pp \to ZZ$ [Nason and Ridolfi, `hep-ph/0606275`]

- $e^+e^- \to$ hadrons [Latunde-Dada, Gieseke and Webber, `hep-ph/0612281`]
  $e^+e^- \to t\bar{t}$ with top decay [Latunde-Dada, arXiv:0806.4560]

- $pp \to Q\overline{Q}$ ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) with spin correlations [Frixione, Nason and Ridolfi, arXiv:0707.3088]

- $pp \to W/Z \to l_1 l_2$ with spin correlations [Alioli, Nason, Oleari and Re, arXiv:0805.4802; Hamilton, Richardson and Tully, arXiv:0806.0290], in the POWHEG BOX too

- $pp \to H$ [Alioli, Nason, Oleari and Re, arXiv:0812.0578; Hamilton, Richardson and Tully, arXiv:0903.4345], in the POWHEG BOX too

- $pp \to H + W/Z$ [Hamilton, Richardson and Tully, arXiv:0903.4345]

Existing implementations

- single-top production, in the s and t channel, with top decay and spin correlations included [Alioli, Nason, Oleari and Re, arXiv:0907.4076], in the POWHEG BOX too. Wt channel almost finished.

- Higgs boson production in vector boson fusion [Nason and Oleari, arXiv:0911.5299] in the POWHEG BOX

All POWHEG implementations for hadronic colliders have been interfaced to both PYTHIA and HERWIG.

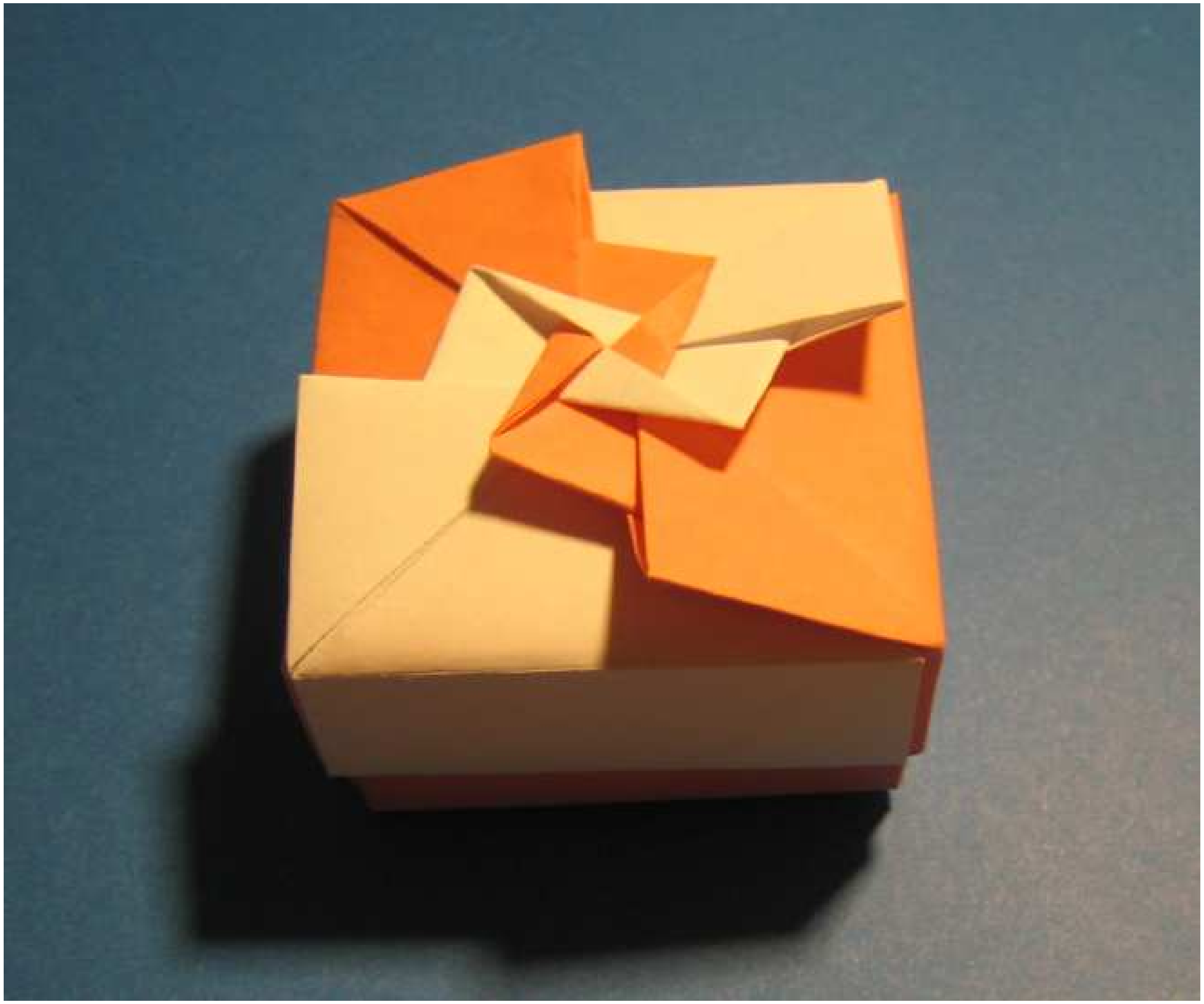
To appear very soon

- $pp \to Z + 1$ jet $\to l\bar{l} + 1$ jet [Alioli, Nason, Oleari and Re] in the POWHEG BOX

- $pp \to VV$ [Hamilton]

- $pp \to Wb\bar{b}$ [Oleari and Reina] in the POWHEG BOX

The POWHEG BOX



The POWHEG BOX

The POWHEG BOX is a public-available computer framework, presented in [Alioli, Nason, Oleari and Re, arXiv:1002.2581], that implements in practice the theoretical construction of the POWHEG formalism, for generic NLO processes, according to the general formulation of POWHEG given in [Frixione, Nason and Oleari, arXiv:0709.2092]

More precisely, the user should only supply:

- ✓ the lists of the Born and real processes (i.e. $sc \to gud \Longleftrightarrow [3,4,0,2,1]$)
- ✓ the Born phase space
- ✓ the Born squared amplitudes, the color-correlated and spin-correlated amplitudes, for all partonic subprocesses
  All these amplitudes are common ingredients of a NLO calculation
- ✓ the real squared amplitude for all the relevant real-emission subprocesses
- ✓ the finite part of the virtual corrections, computed in conventional dimensional regularization or in dimensional reduction
- ✓ the Born color structures in the limit of large number of colors.

All the rest will be done **automatically**!

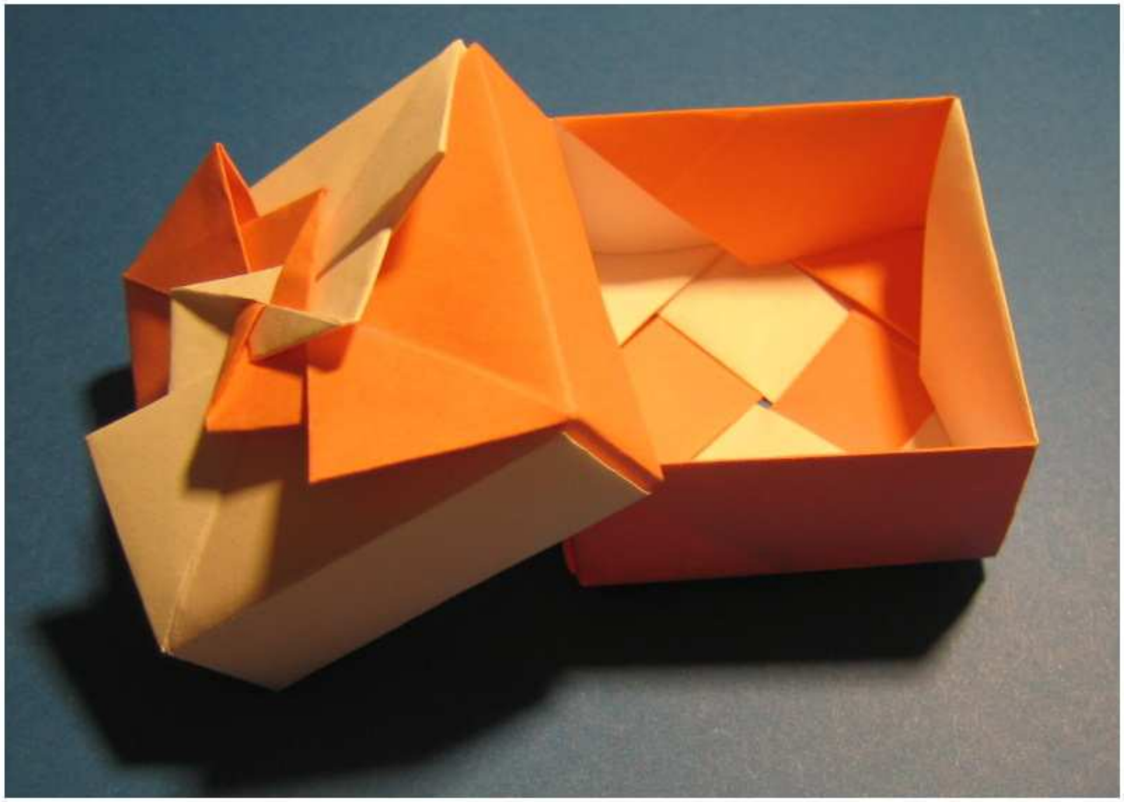
The POWHEG BOX

The user should not worry about

- ✓ the phase space for initial-state radiation and final-state radiation (i.e. the phase space for real emission)
- ✓ the combinatorics, the identification of all singular regions in the real amplitude R, the soft and collinear limits, the calculation of all the counterterms
- ✓ the calculation of the differential NLO cross section
  Spinoff: NLO results using the FKS subtraction scheme
- ✓ the calculation of the upper bounds for the generation of radiation (for an efficient generation of the Sudakov-suppressed events)
- ✓ the generation of radiation
- ✓ writing the event into the Les Houches interface (to communicate with the LO Shower Monte Carlo programs)

The user has only to know in which format to supply the ingredients listed before.

The POWHEG BOX



No need to open the BOX!

The POWHEG BOX today

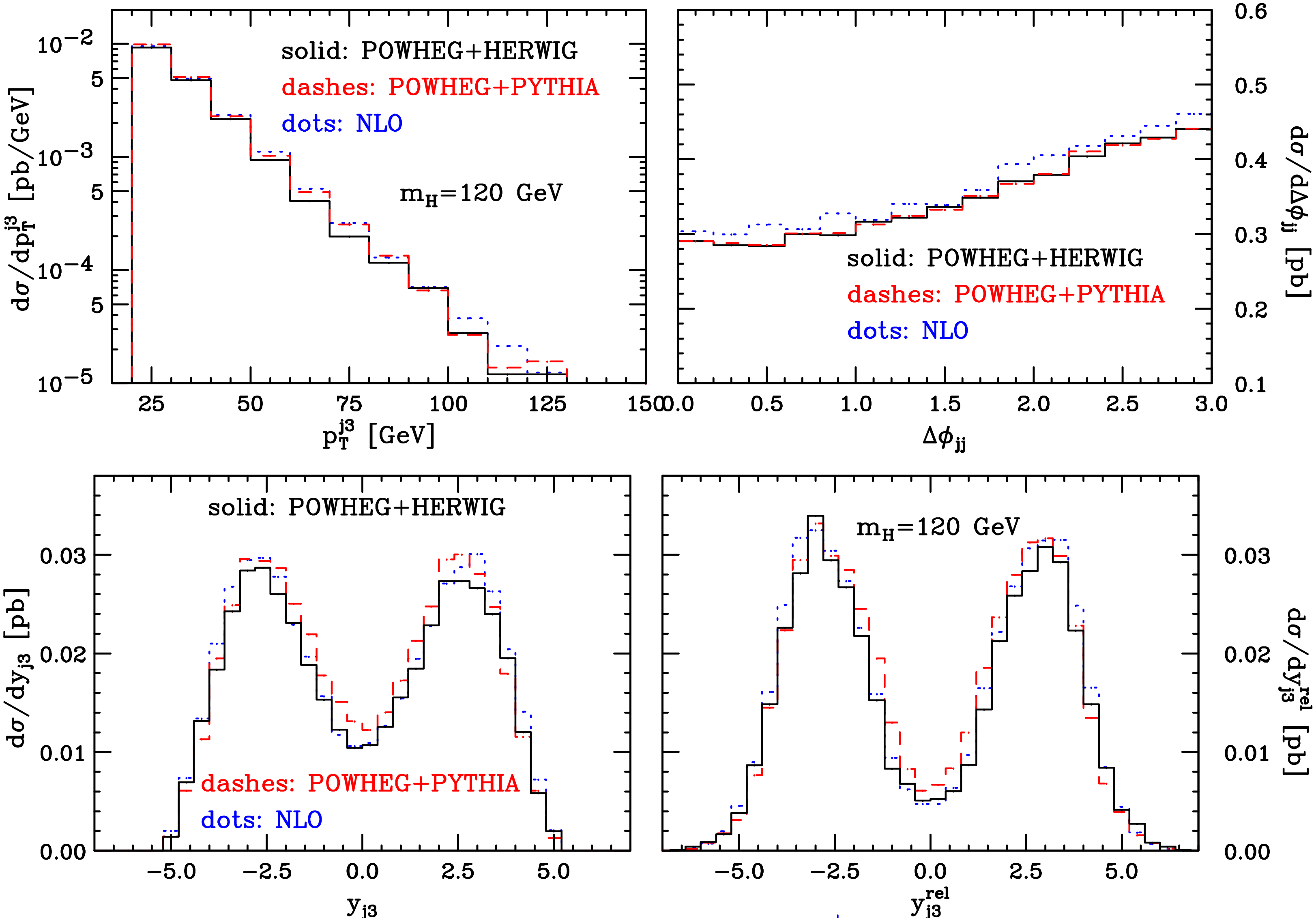
The POWHEG BOX is a package in evolution.

As new processes are implemented in the BOX, new problems will probably need to be solved and the code will change accordingly.

Right now, in the code, you can find

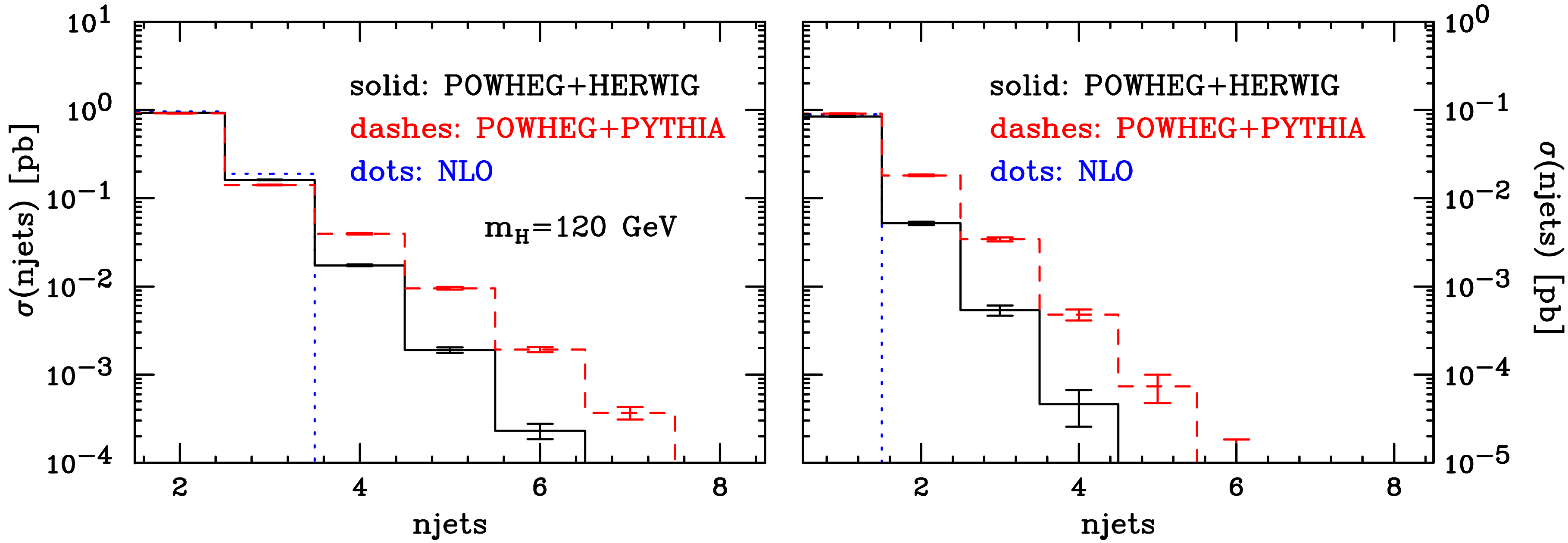
- W production: $pp(\bar{p}) \to W \to l\nu_l$ $\Longleftarrow$ Born zero diagrams
- Z production: $pp(\bar{p}) \to Z \to l^- l^+$
- Higgs production in gluon fusion $\Longleftarrow$ tuning of the real cross section
- Higgs production in VBF $\Longleftarrow$ tagging parton lines
- $Z + 1$ jet: $pp(\bar{p}) \to Z + 1\,\text{jet} \to l^- l^+ + 1\,\text{jet}$ $\Longleftarrow$ divergent Born

Higgs boson in VBF



$$y_{j_3}^{\rm rel} = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$$

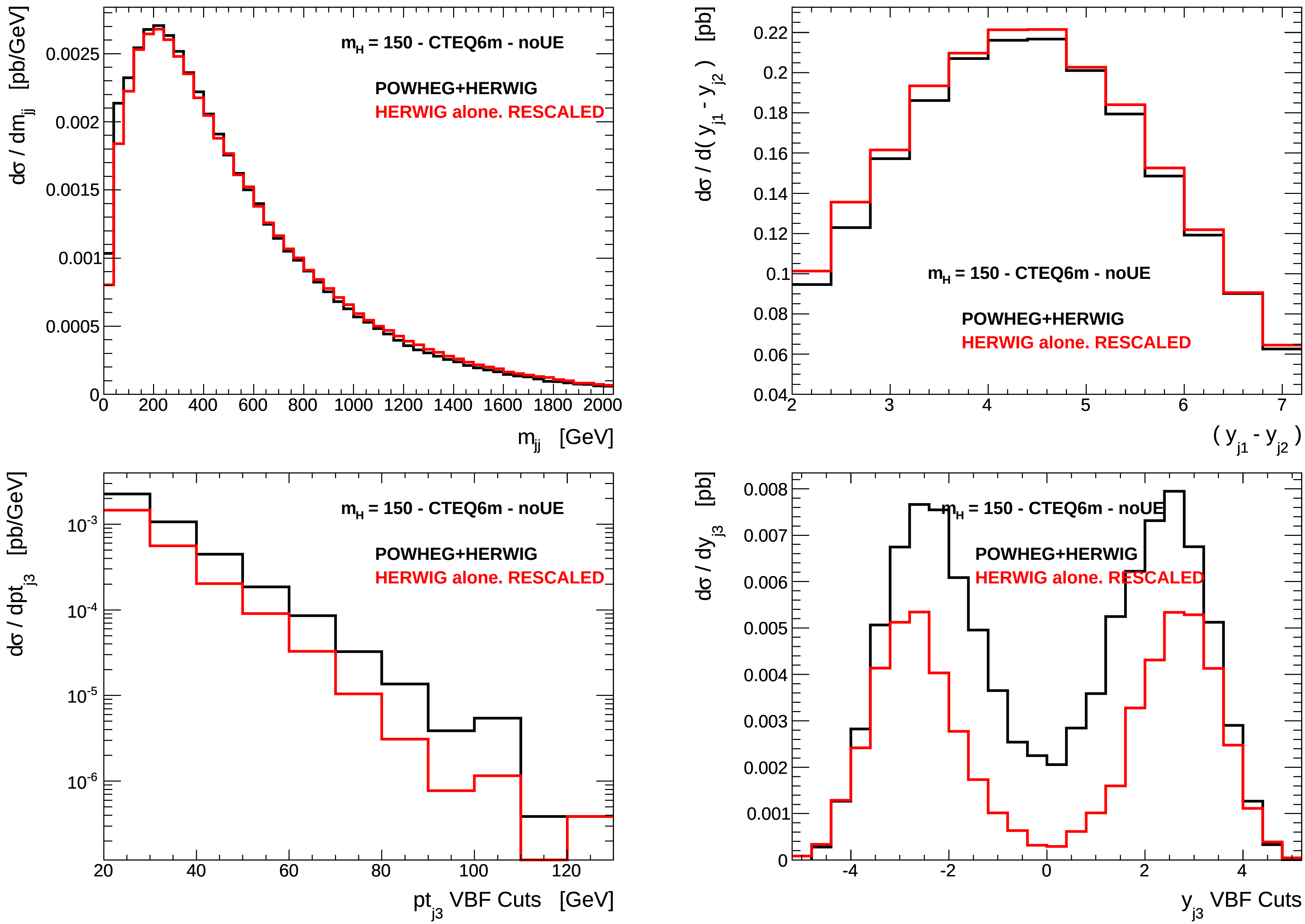
Higgs boson in VBF



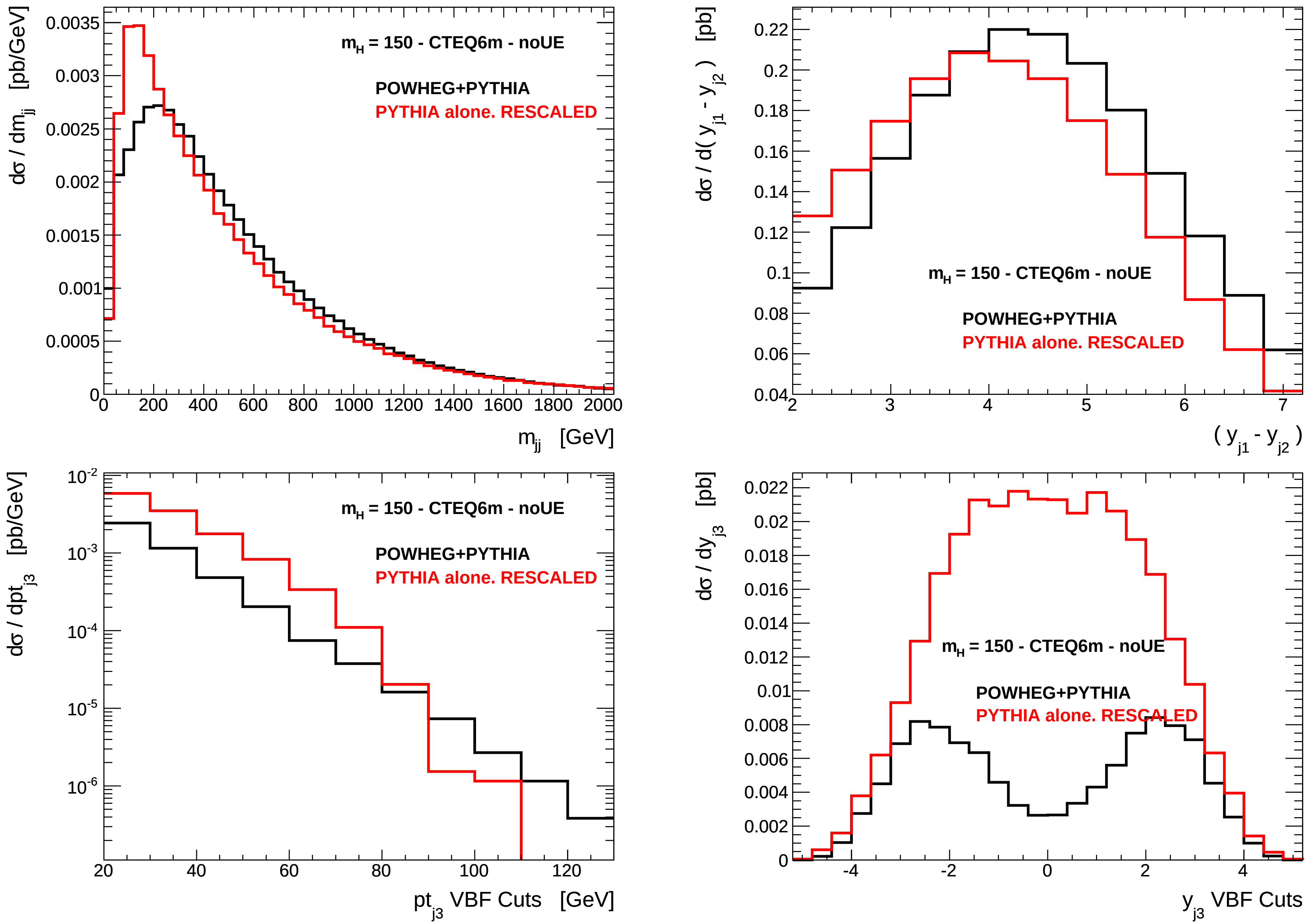
$$p_{Tj} > 20\ \mathrm{GeV}, \qquad |y_j| < 5$$

$$p_T{}^{\mathrm{tag}} > 30\ \mathrm{GeV}, \qquad |y_{j_1} - y_{j_2}| > 4.2\,, \qquad y_{j_1} \cdot y_{j_2} < 0\,, \qquad m_{jj} > 600\ \mathrm{GeV}$$

veto jet : $\quad \min\left(y_{j_1}, y_{j_2}\right) < y_j < \max\left(y_{j_1}, y_{j_2}\right)$

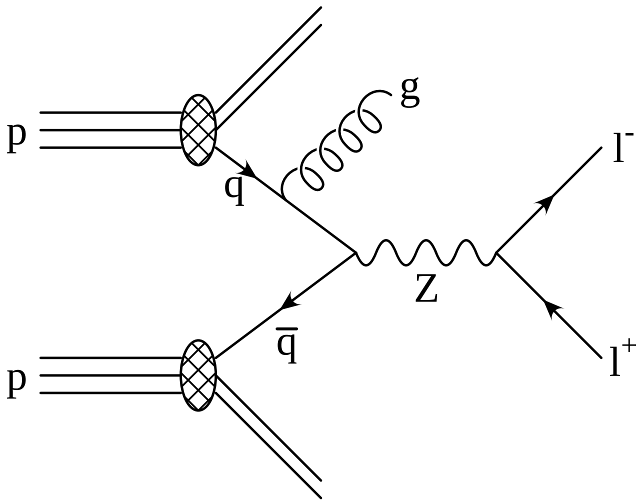


Neither HW alone nor PY alone are expected to describe correctly the 3rd jet. HW results rescaled to the NLO total Xsec



Harder PY jets “mimic” tagging jets. Wrong shapes for m_{jj} and $(y_{j1} - y_{j2})$. Same for y_{j3}. PY results rescaled to the NLO total Xsec

$Z + 1$ jet



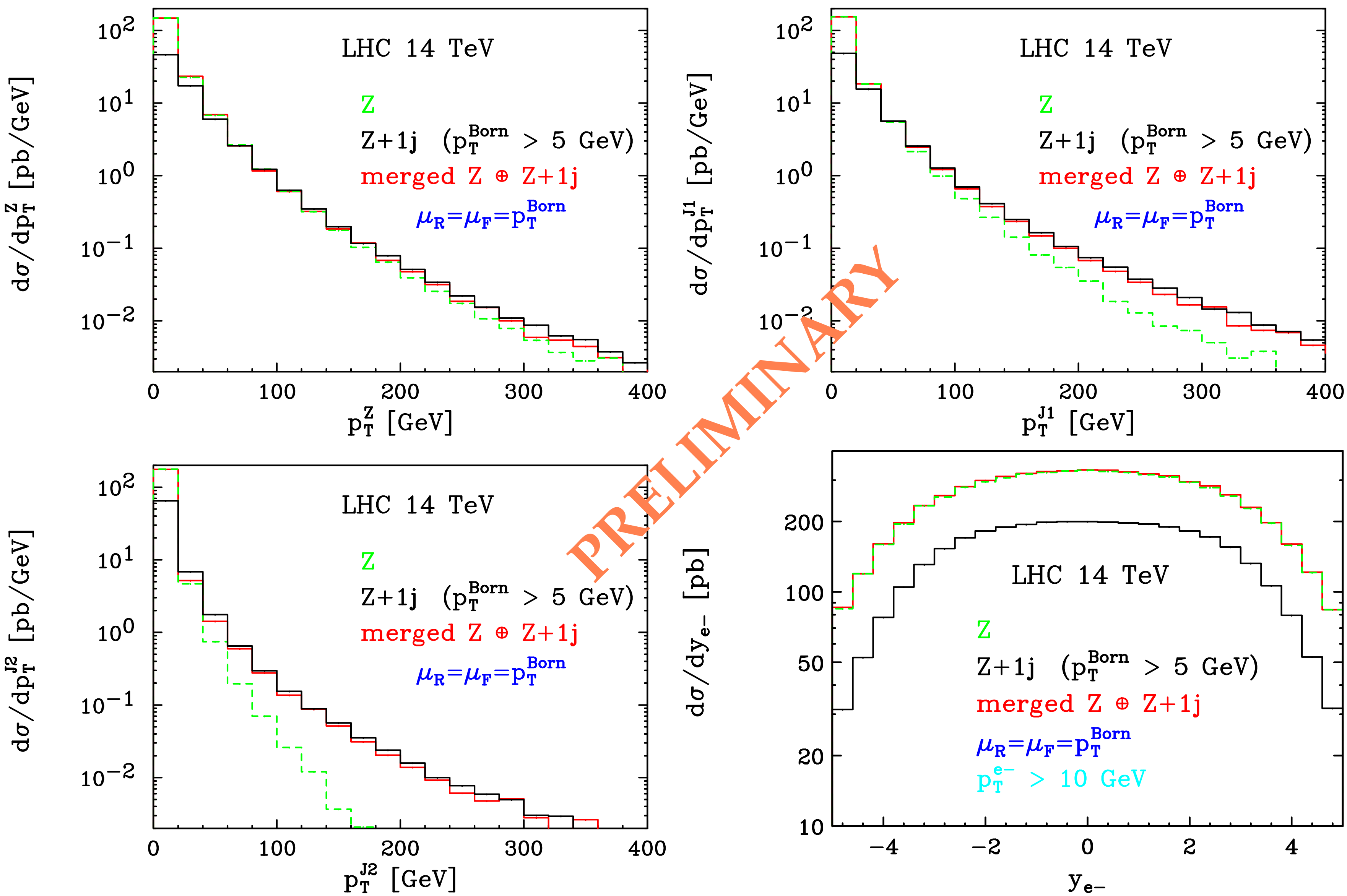
New problem to solve: the Born contributions are divergent.

POWHEG starts from a Born diagram and attaches radiation.

Simplest solution: introduce a cutoff. Generate events starting from partonic Born events with $p_T^{\rm Born} > p_T^{\rm min}$

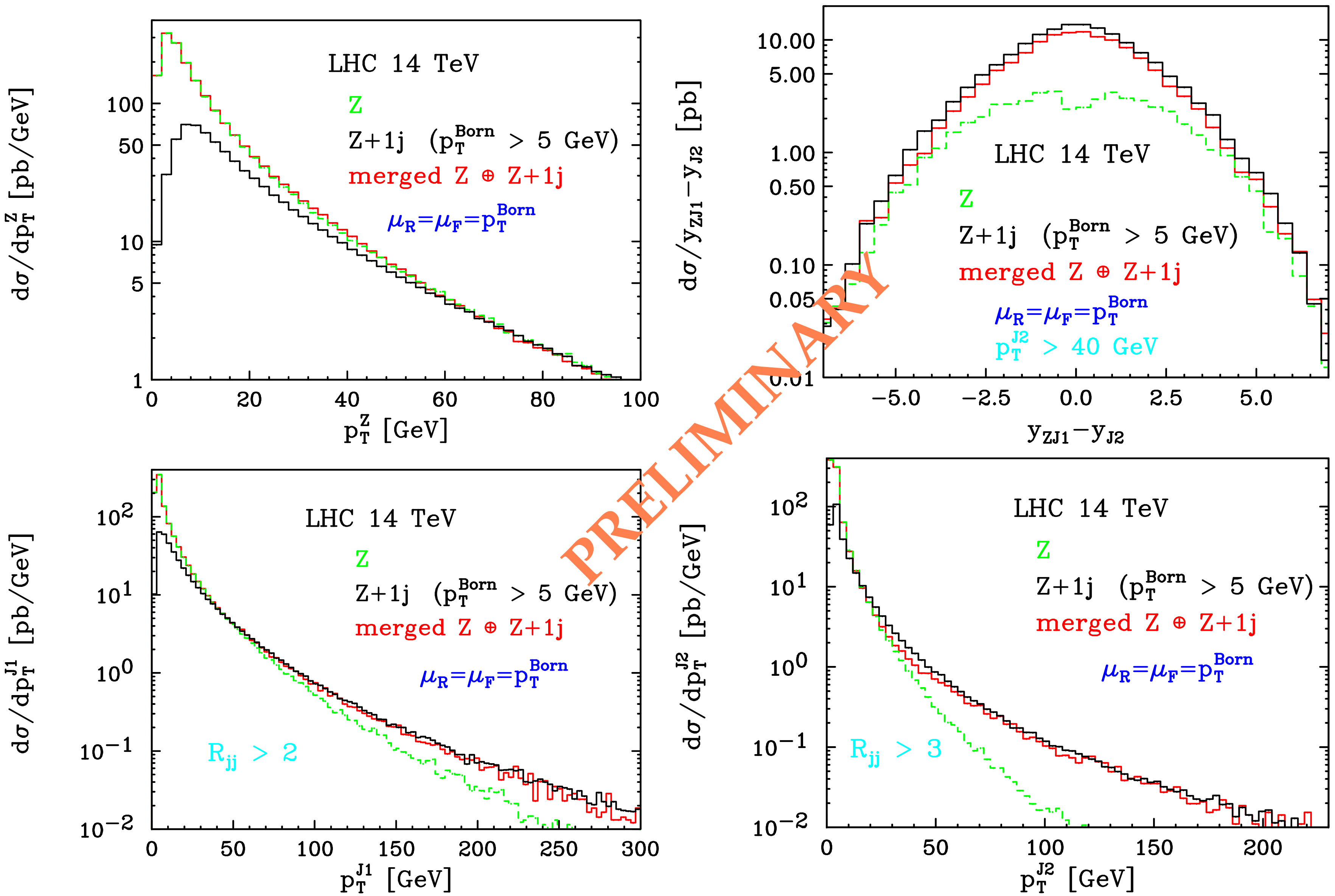
- Study the effect of the cutoff at the partonic Born level on showered events
- Find a way to merge consistently NLO Z and $Z + 1$ jet events.

Preliminary merged Z and $Z + 1$ jet events



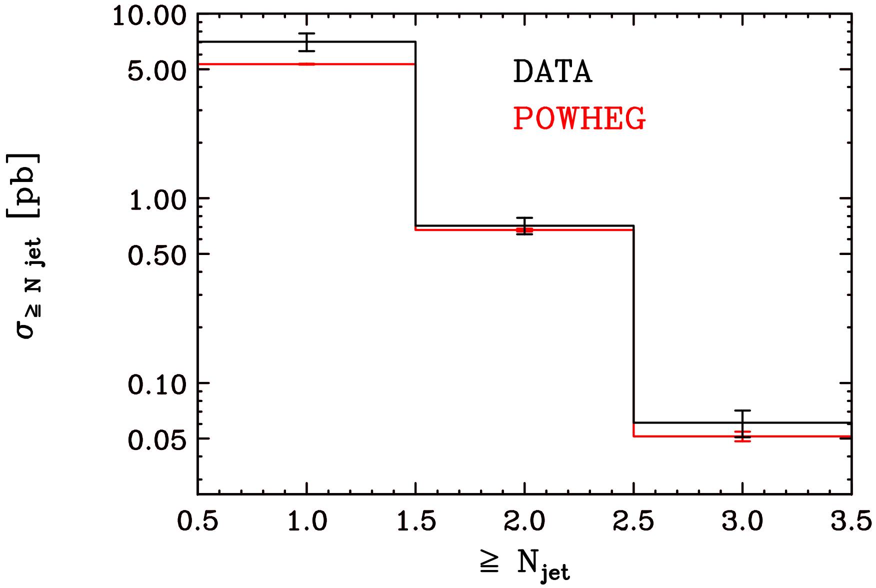
All results showered by HERWIG

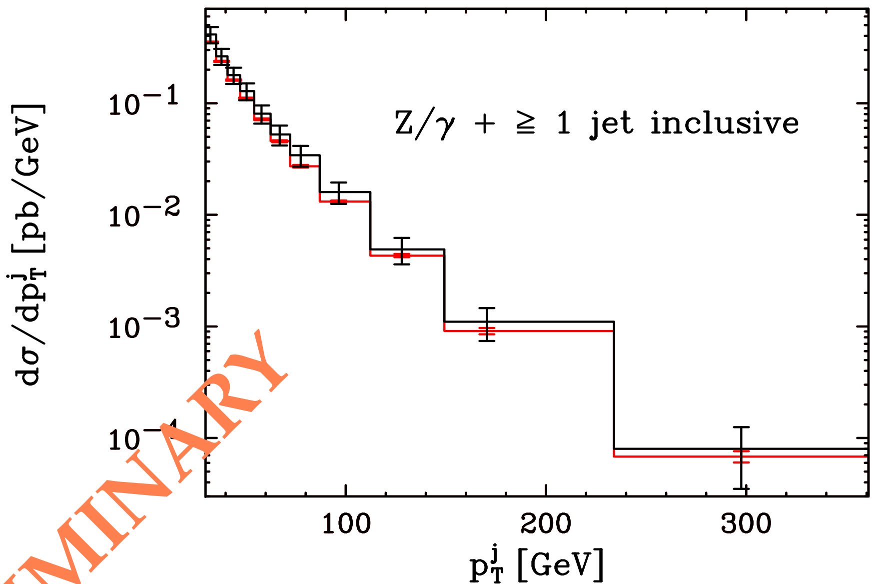
Preliminary merged Z and $Z + 1$ jet events

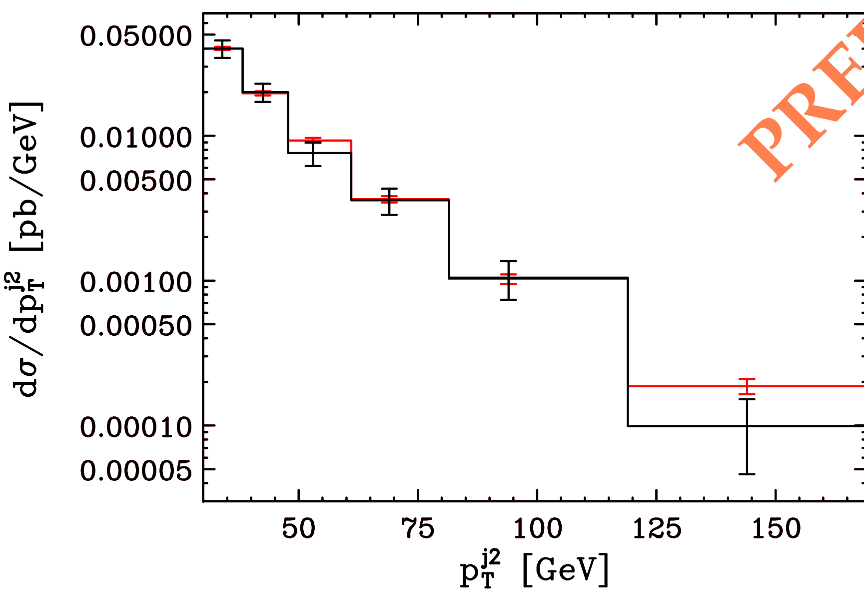


All results showered by HERWIG

Preliminary: CDF results for $Z/\gamma \longrightarrow e^+e^-$



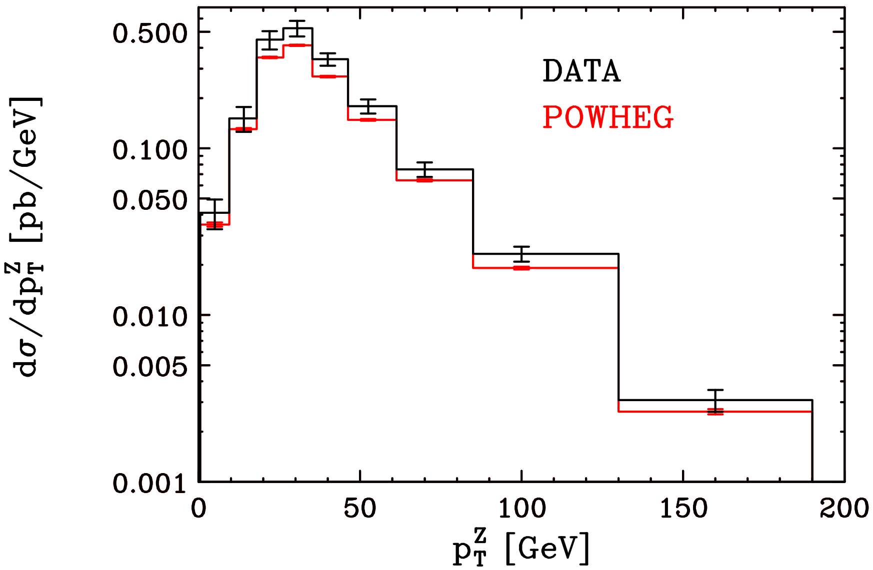


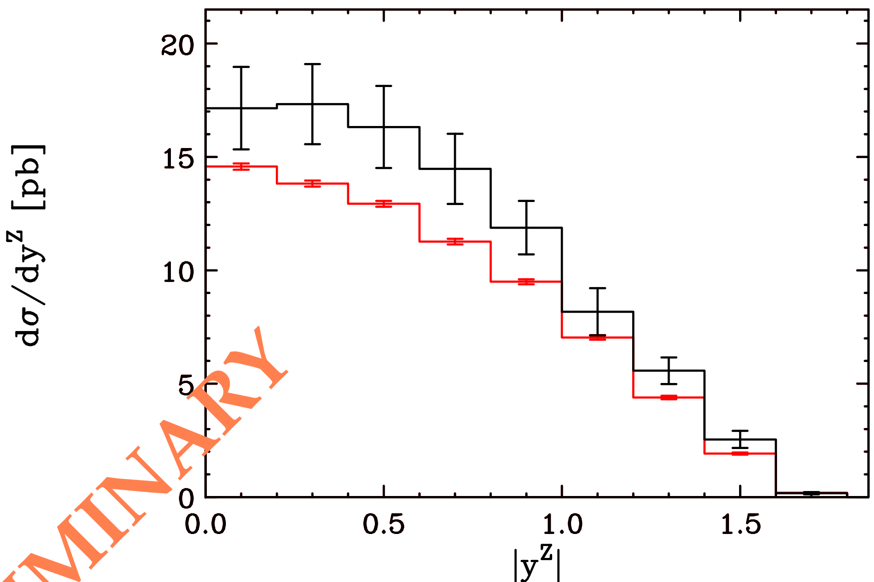


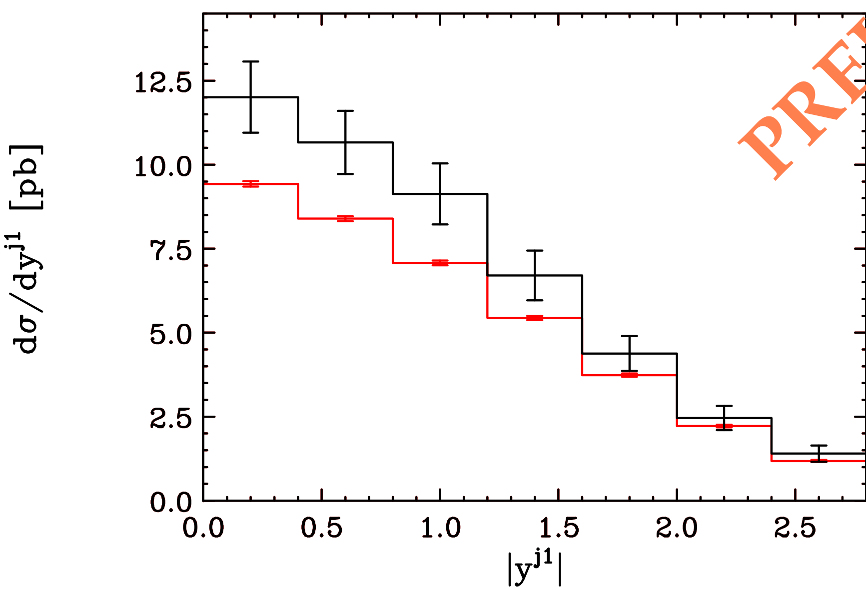
- $p\bar{p}$ @ $\sqrt{S} = 1.96$ TeV
- $|y^j| < 2.1$ $\quad$ $p_T^j > 30$ GeV
- 66 GeV $< m_{ee} <$116 GeV
- $p_T^e > 25$ GeV
- $|y^{e_{1,2}}| < 1$ $\quad$ $1.2 < |y^{e_2}| < 2.8$
- $\Delta R_{e,j} > 0.7$

All results showered by PYTHIA

Preliminary: D0 results for $Z/\gamma \to \mu^+\mu^-$







- $p\bar{p}$ @ $\sqrt{S} = 1.96$ TeV
- $|y^j| < 2.8 \qquad p_T^j > 20$ GeV
- 65 GeV $< m_{\mu\mu} <$115 GeV
- $p_T^{\mu} > 15$ GeV
- $|y^{\mu_{1,2}}| < 1.7$
- $\Delta R_{e,j} > 0.5$

All results showered by PYTHIA

Conclusions

- ✓ It is relatively easy to add new processes in the POWHEG BOX.
- ✓ No need to know how it works but only how to "communicate" with it.
- ✓ Please, feel free to get in touch with us if you want to insert new NLO calculations into the POWHEG BOX.
- ✓ The code can be downloaded from

  `http://moby.mib.infn.it/~nason/POWHEG/`

  where we keep a SVN version too, with all the recent upgrades.